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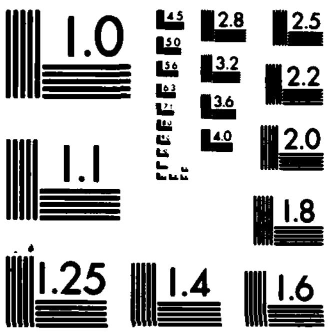

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Final Report

To

The Office of Naval Research

SUPERCONDUCTING DEVICES

Contract #N00014-76-0-0526

Contract Period: December 1,1975 - November 30, 1980

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Introduction

All of the major results of the research that was carried out under this contract have been extensively reported in the scientific literature. A list of these publications is given at the end of this report as well as the Ph.D theses that were completed with full or partial support by this ONR contract.

The major program accomplishments that should be highlighted and summarized in this final report are the followinmg: (1) An extensive and complete analysis of the modes of operation, circuit optimization and sensitivity limits of the rf biased SQUID was completed. (2) Advanced state-of-the-art microfabrication techniques were developed and applied to the production and study of superconducting thin film microbridges, with concentration on submicron superconductor-normal metal-superconductor junctions. (3) A new reactive ion beam oxidation procedure was developed and applied, with the aid of micro-lithography techniques to the the production of very high quality, niobium-niobium oxide tunnel junctions with submicron dimensions.

RF SQUID Analysis: At the beginning of this program, a major effort was directed towards an extensive study of the circuit optimization and sensitivity limits of the rf biased SQUID. Initial efforts were concerned with the most common type of rf SQUID which is operated at relatively low frequency in what is known as the hysteretic or large critical current regime. This work was then extended to consider both the high frequency regime, where the bias frequency matches or exceeds the natural response frequency of the SQUID ring, and the low critical current or inductive mode of operation. This effort combined experimental measurements, theoretical calculations and extensive digital simulations. The mode of operation, optimum

circuit condition and basic sensitivity limits were established for all types of rf SQUIDs employing good Josephson-like weak links. It was demonstrated that maximum inherent sensitivity, is achieved by operating the SQUID at a frequency ω-R/L and critical current $i_c < \phi_0/2\pi L$. Here R and L are the weak link resistance and SQUID ring inductance respectively. It was shown that for an ideal Josephson weak link, the maximum possible SQUID sensitivity is set only by the uncertainty principle. This gives a limiting magnetic energy sensitivity of $\approx 7 \times 10^{-34}$ Joules/Hz.

Microfabrication and Study of Thin Film Josephson Microstructures:

This project was an effort to develop advanced thin film deposition and microfabrication capabilities suitable for producing Josephson thin film microstructures. The effort had the dual objectives of producing new types of improved weak links for quantum devices and providing controlled structures for the detailed study of basic Josephson phenomena. The development of such capabilities was essential to our quantum superconductivity research program and, as a practical matter, tended to occupy a very major portion of the resources of the program.

Our initial effort in microfabrication began with producing thin film, micron size, uniform thickness microbridges by photolithography. We then expanded our capabilities to the point where, for example, we could produce micron and sub-micron variable thickness In and Pb microbridges via several alternative procedures including masking and oblique evaporation, photolithography and electron-beam lithography combined with ion milling. Since it was clear that, in general, sub-micron dimensions are required for optimum weak link performance, we made a major point of developing a credible capability in electron-beam lithogrpahy. This lithography effort initially focused on adapting an SEM for lithography usage, later it involved using

the resources of the National Submicron Facility, established at Cornell in 1977. With the use of electron beam lithography,techniques were developed which could produce simple microstructure with all dimensions < 2000 Å, which is still state-of-the-art in electron-beam lithography.

In addition to producing "traditional" type weak links from the soft superconducting materials such as I_N, Pb, etc. and from the refractory superconductor Nb we also sought to explore new concepts of Josephson structures which were not being actively investigated elsewhere. We particularly emphasized the production of very small normal metal tunnel junctions. The geometry of these SNS junctions is that of a very narrow (≈ 2000 Å), short (≈ 2000 Å) normal metal thin film strip connecting two superconducting thin film banks. Such junctions are a possible alternative for certain research applications where either SIS tunnel junctions or microbridges are normally employed. Their investigation was also attractive from the basic information that could be obtained concerning the microphysics of various aspects of Josephson phenomena. The fact that these structures can be considered to be composed of a gapless superconductor also meant that a detailed check could be made for the first time of the time dependent Ginzberg-Landau (TDGL) equations in a regime where they were expected to be valid.

The approximately 0.2 μm SNS structures that were produced in this project had relatively high impedance, $R \gtrsim 1\ \Omega$, and were found to exhibit dc and ac Josephson behavior which compared quite favorably with any that had been reported for superconducting microbridges. But by varying the dimensions of these junctions in a controlled manner, we were also able to determine that there was an intrinsic response time, inversely dependent on length, for these junctions that limited their high speed or high frequency

behavior. This finding was in semi-quantitative agreement with the predictions of the TDGL theory. We concluded from this work that to achieve a frequency response with SNS junctions of better than 100 GHz would require that the junction be fabricated with all dimensions less than 100 nm, unless the junction impedance was allowed to drop to uselessly low levels.

The study of SNS junctions also yielded other interesting results concerning non-equilibrium phenomena in Josephson junctions. Of particular interest was the rather spectacular microwave enhancement of supercurrent that could be obtained under proper conditions. This effect in SNS junctions is not explained by the generally accepted Eliashberg mechanism for microwave enhancement of the energy gap. This is so since these junctions do not have a gap. Instead our results show that the explanation lies in the spatial averaging of the electrons at each energy level over the length of the bridge. This experiment appears to be the first that definitely proved that the Eliashberg/Chang-Scalapino theory is not the complete story on the Dayem effort. Instead, more work is clearly needed to fully explain this phenomena.

Production of High Quality Nb-Nb Oxide Submicron Josephson Junctions:

In the last several years of this contract a major focus of the program was the fabrication of high quality Nb tunnel junctions. We began this project because it was our opinion that the advancement of superconductor electronics required stability and reliability superior to that provided by the lead alloy system pioneered at IBM and adopted extensively elsewhere. Consequently we initiated a major effort to solve the performance problems previously found with Nb junctions, realizing that refractory (e.g., Nb, Nb alloy, etc.) superconducting films are very considerably

more rugged and stable than the soft (Pb, Pb alloy, etc.) superconducting films. The results that we obtained as well as results obtained concurrently elsewhere, clearly demonstrated the validity of our focus on Nb junctions. It is safe to say that the all lead junction will soon be nearly completely discarded in favor of the superior Nb-NbO_x - Pb alloy junctions.

The major feature of the results of the Nb tunnel junction research was the achievement of very good quality I-V characteristics, very low leakage currents, etc., with a fabrication process compatible with integrated circuit technology. The new aspect of this work involved an ion beam cleaning and reactive ion beam oxidation step for the formation of the tunnel barrier. This oxidation method has major advantages over the widely used plasma oxidation process. The ion beam oxidation step greatly reduces the scattering of impurities onto the junction during the oxidation step. This makes the process more reliable and allows thinner barriers to be produced while maintaining good quality I-V characteristics. Thin barriers mean high critical current densitites and high critical current densities result in high speed performance. With Nb-NbO_x-PbBi junctions we achieved record critical current densities in excess of 10^6 amps/cm^2, while maintaining acceptable junction characteristics. Current densities of this size correspond to an intrinsic junction switching time of the order of 0.1 psec. The achievement of such high current densities now allows, for the first time, investigations into intrinsic response limits of junctions.

The stability of these junctions was found to be quite good, both during room temperature storage and after multiple cycles between room temperature and helium temperature. The only junction failures that were

experienced had been with submicron area junctions and were due to electrical discharges, a universal problem with submicron systems.

In order to obtain the high impedance needed for many tunnel junction applications, it is necessary to produce very small area junctions, thereby minimizing the shunt capacitance. To produce such junctions we successfully developed a technique of fabricating tunnel junctions on the faceted edge of a niobium film. In this manner, tunnel junctions with area of the order 10^{-9} cm^2 can be produced with photolithography technology (1-2 μm minimum linewidth). The I-V characteristics were as good as those obtained with larger, overlap geometries. This edge junction technique is quite compatible with integrated circuit technology; that is compatible with a number of processing steps occurring between deposition of the base-electrode and the formation of the barrier and deposition of the counter-electrode. The technique actually resulted in better control of the junction area than could be obtained with overlap geometries since one dimension of the junction is very precisely determined by the niobium film thickness.

Finally we were successful in developing an electron beam lithography process which was compatible with the edge junction technique. Consequently, we were able to produce Nb-NbO_x-PbBi tunnel junctions with areas as small as 2×10^{-10} cm^2, and with very satisfactory I-V characteristics. Such junctions are just what is required for Josephson device applications in the millimeter and submillimeter frequency ranges and for the production of ultra-high sensitivity Dc SQUIDs.

Device Research with Submicron Josephson Junctions:

Since the Nb-PbBi tunnel junctions that we were able to produce were equal to or better than any Josephson junction being fabricated elsewhere,

experiments concerned with the application of these junctions in demanding areas of Josephson device research were warranted. The two non-digital applications of Jospehson junctions that are of most current interest are the SIS quasi-particle mixer and the dc SQUID. Of the two, the SIS mixer demands the most from the junction; very high quality I-V characteristics, high current density for high frequency response, and very small junction area for high device impedance. These were the characteristics of our tunnel junctions.

We began experiments investigating the performance of our submicron Nb-NbO_x-PbBi tunnel junctions as 55 GHz mixers. The experimental program was a systematic study of the effects of junction parameters and device configuration upon mixer performance. Since these junctions are superior in one way or another to those being employed in mixer experiments elsewhere, our expectation was that this program will yield some definitive results concerning the optimization of this type of very promising device. At the end of the contract period, in preliminary work, we had achieved 55 GHz mixer noise temperatures of less than 10 K, and mixer insertion loss of less than 10 dB with junctions of less than best quality. These results were comparable to those currently being reported in the literature and are approaching the quantum limit. Significant improvements could be expected with further work, owing to the superior quality of our junctions.

Further details on all these and other research results can be found in the following publications:

Publications

1. L. D. Jackel, J. M. Warlaumont, T. D. Clark, J. C. Brown, R. A. Buhrman, and M. T. Levinson, "Superconducting Weak Link Current-Phase Relations", Appl. Phys. Lett. 28, 353 (1976).

2. L. D. Jackel, W. H. Henkels, J. M. Warlaumont, and R. A. Buhrman, "Current-Phase Relations as Determinant of Superconducting Thin-Film Weak-Link I-V Characteristics", Appl. Phys. Lett. 29, 214 (1976).

3. R. A. Buhrman and L. D. Jackel, "Performance Factors in rf SQUIDS - High Frequency Limit", IEEE Transactions on Magnetics MAG-13, 879 (1977).

4. R. A. Buhrman, "Noise Limitations of rf SQUIDS", in SQUID (Walter de Gruyter & Co., New York) p. 395 (1977).

5. J. T. C. Yeh and R. A. Buhrman, "Capacitively Shunted Variable- Thickness Microbridges", Appl. Phys. Lett. 31, 362 (1977).

6. J. T. C. Yeh and R. A. Buhrman, "Superconducting Lead Variable-Thickness Microbridges", J. Appl. Phys. 48, 5360 (1977).

7. J. M. Warlaumont and R. A. Buhrman, "Planar SNS Microbridges", IEEE Transaction on Magnetics MAG-15, 570 (1979).

8. J. M. Warlaumont, J. C. Brown, and R. A. Buhrman, "Response Times and Low Voltage Behavior of SNS Microbridges", Appl. Phys. Lett. 34, 415 (1979).

9. J. M. Warlaumont, J. C. Brown, T. Foxe, and R. A. Buhrman, "MicrowaveEnhanced Proximity Effect in Superconductor-Normal-Metal-Superconductor Microjunctions", Phys. Rev. Lett. 43, 169 (1979).

10. A. W. Kleinsasser and R. A. Buhrman, "High Quality Submicron Niobium Tunnel Junctions by Reactive Ion Beam Oxidation", Appl. Phys. Lett. 32, 841 (1980).

11. A. W. Kleinsasser and R. A. Buhrman, "Fabrication of Josephson Tunnel Junctions by Reactive Ion Milling", Proc. 9th Int'l Conf. on Electron and Ion Beam Science, ed. R. Bakish (St. Louis, MO., 1980).

Ph.D Theses

1. J. M. Warlaumont, "Properties of Superconductor-Normal Metal-Superconductor Microbridges", Ph.D Thesis, Cornell University, Ithaca, NY (January 1980).

2. A. W. Kleinsasser, "Small Area Niobium Tunnel Junctions with Reactive Ion Beam Oxidation", Ph.D Thesis, Cornell University, Ithaca, NY (January 1981).

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